Naturalness Principles Supersymmetry and Tenable Physics Motivations for HEMC's

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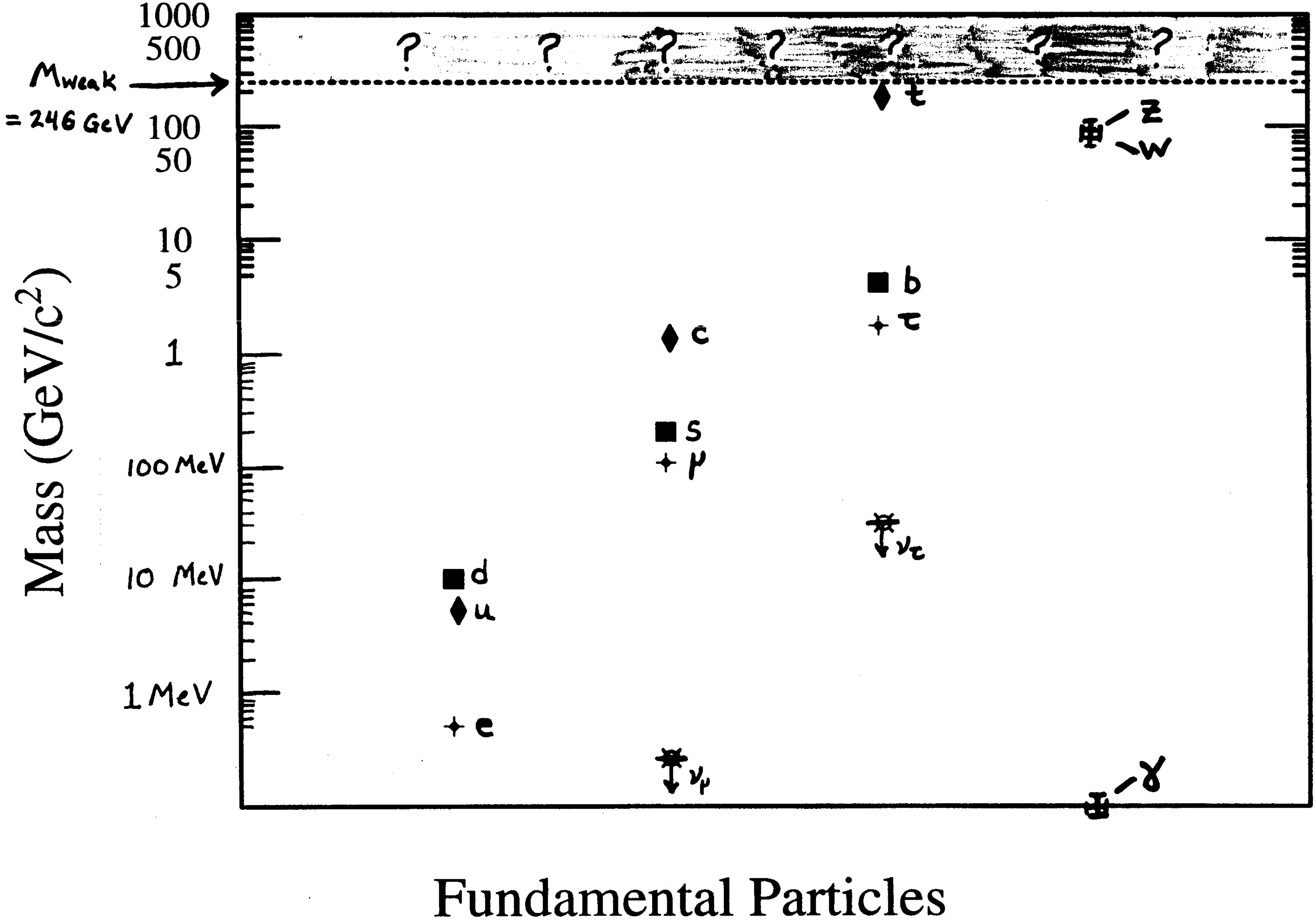
Outline:

1. Naturalness and Superpartner Masses
   - Why are superpartners "heavy"
   - Fundamental Scales
   - The naturalness problem
   - 3 Solutions
   - Measures of Fine-tuning
   - Fine tuning in the MSSM
   - Expected values of superpartner masses
   - Variations on the MSSM

Despite continuing searches for superpartners we have not observed a "doubling" of the spectrum...

Should we be surprised?

Can this continue?



Mass (GeV/c²)
1000
500
M_weak
= 246 GeV
100
50
10
5
1
100 MeV
10 MeV
1 MeV
? ? ? ? ? ? ?
t
Z
W
b
τ
c
s
μ
d
u
e
ν_μ
ν_τ
γ
Fundamental Particles

Fundamental Energy Scales

$\hbar = c = 1$

Energy

$M_{planck} \sim 10^{19}$ GeV

$F_G \sim G_N \frac{m_1 m_2}{r^2}$

$G_N = \frac{1}{M_{pl}^2}$

$v \sim 246$ GeV

Weak-scale

i.e. the scale of EW symmetry breaking

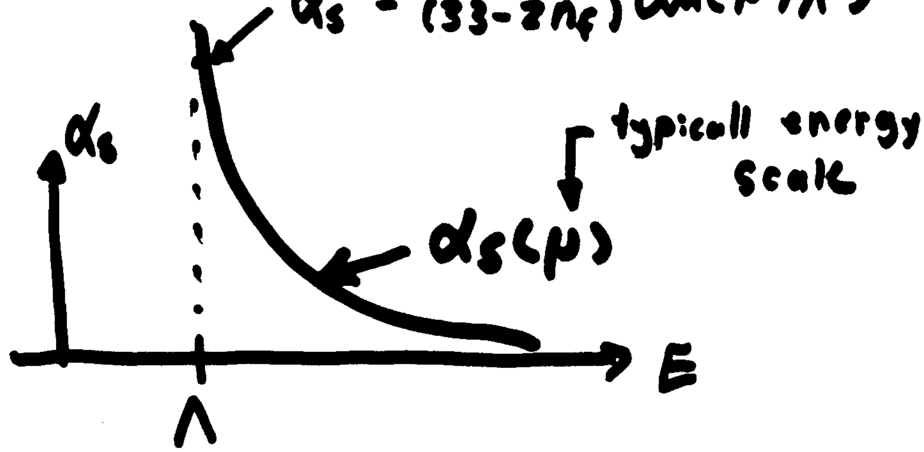
$G_F \sim \frac{1}{v^2} \simeq 246$ GeV

$M_W \sim g v$

$\langle \phi \rangle = v$

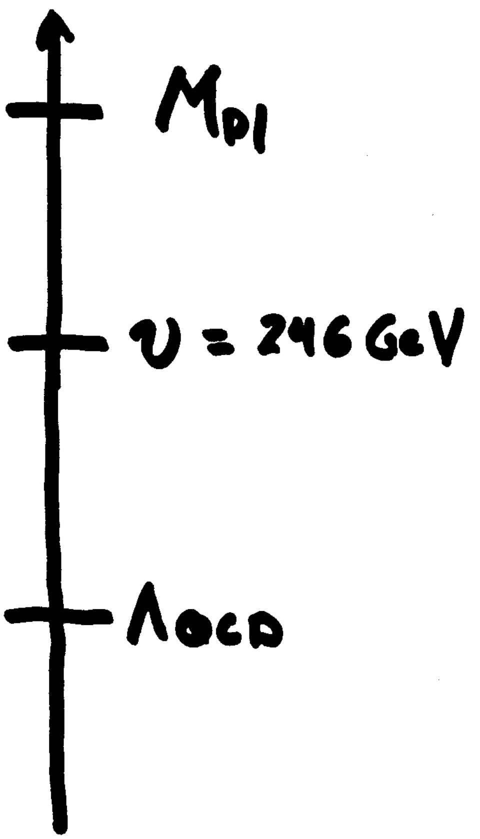
Λ_{QCD}

$\alpha_s = \frac{12\pi}{(33-2n_f)\ln(\mu^2/\Lambda^2)}$



All of the masses in the SM are related to the two fundamental scales v, Λ_{QCD} by dimensionless couplings

The Hierarchy Problem & The Naturalness Problem



Hierarchy Problem

why is $v \ll M_{Pl}$?

Naturalness Problem

If we impose $v \ll M_{Pl}$ is this stable.

By comparison $\Lambda_{QCD}/M_{Pl} \ll 1$ has no such problem:

Hierarchy: $$\frac{1}{g_s^2(\mu)} = \frac{1}{g_s^2(\mu')} + \frac{b}{(4\pi)^2} \ln(\mu'/\mu)$$

$$\Rightarrow \Lambda_{QCD} \sim M_{Pl}\, e^{-\# \frac{(4\pi)^2}{g^2(M_{Pl})}}$$

Naturalness: Symmetry = (broken) scale invariance

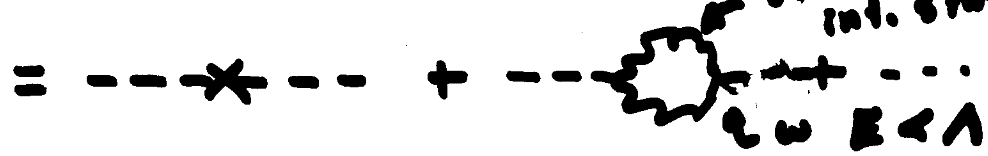
If we change $g_s(M_{Pl})$ by a little bit Λ_{QCD}/M_{Pl} is still $\ll 1$

The Naturalness Problem in the SM

or why the SM can't be the correct theory at energies $\gg v \sim 246$ GeV

- Assume the SM is a good theory up to some scale Λ
- Compute the Higgs mass (a vev)

$$m_H^2 = m_{0H}^2 + \delta m_H^2$$



$$m_H^2 = m_{0H}^2 + g^2 \Lambda^2$$

similiarly

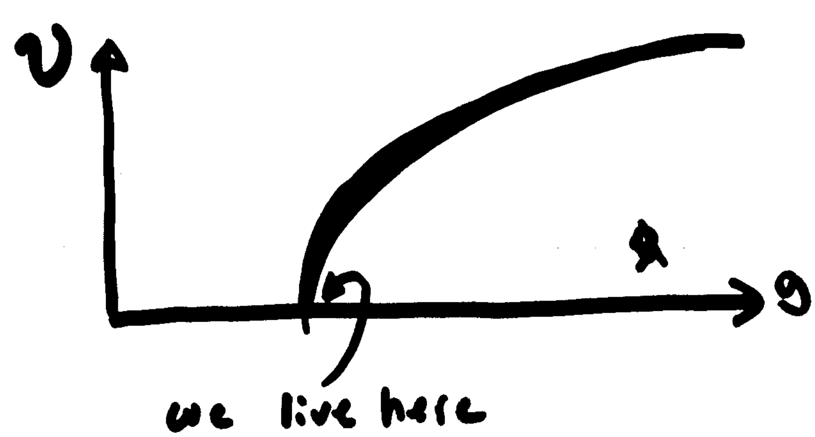
$$v^2 = -v_0^2 + g^2 \Lambda^2$$

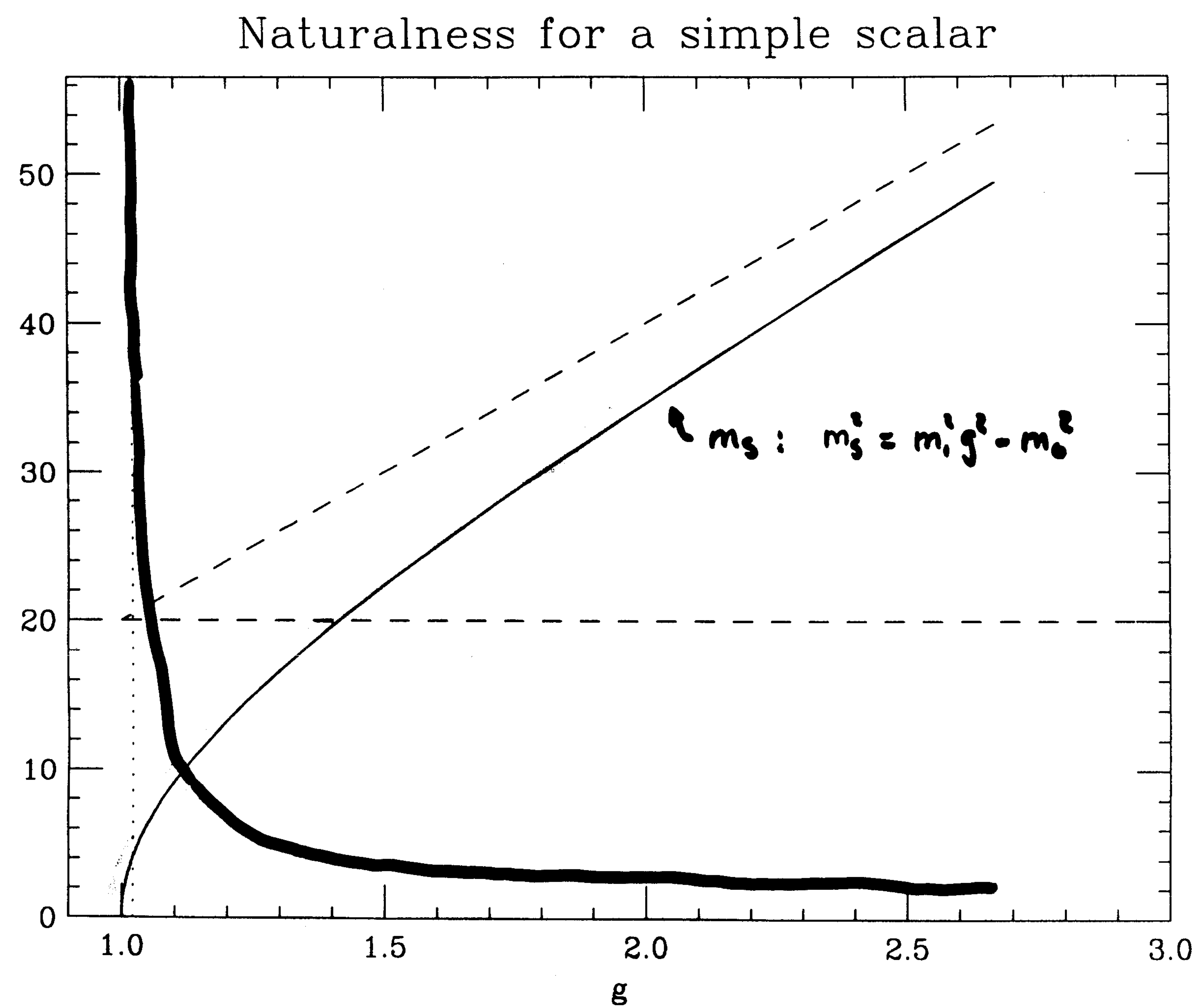
Measured as $(246 \text{ GeV})^2$ ↑ ; $g^2 \sim 1$; Λ^2 e.g. $(10^{18} \text{GeV})^2$

Requires

$$(246)^2 = -(10^{18})^2 + (10^{18})$$

Need to cancel to 1 part in 10^{34}




Naturalness for a simple scalar
50
40
30
20
10
0
1.0
1.5
2.0
2.5
3.0
g
m_s : $m_s^2 = m_1^2 g^2 - m_0^2$

THE PHYSICS BEYOND THE SM i.e. at $E \gtrsim \mathcal{O}(100\,\text{GeV})$ can be classified by their solution to this problem. (why $\frac{v}{M_{pl}} \ll 1$)

I Strong Dynamics (Sym = Scale Inv)

The Higgs is not fundamental $\phi \sim f\bar{f}$

v is from broken scale invariance like Λ_{QCD} in QCD

Examples : Technicolor , Topcolor

II Extra Dimensions (Change M_{pl})

M_{pl} is not what you think it is

n - compact dim. of radius R

$$M_{pl} = M_F (M_F R)^{n/2} \quad \text{if } M_F \sim 1\,\text{TeV}$$

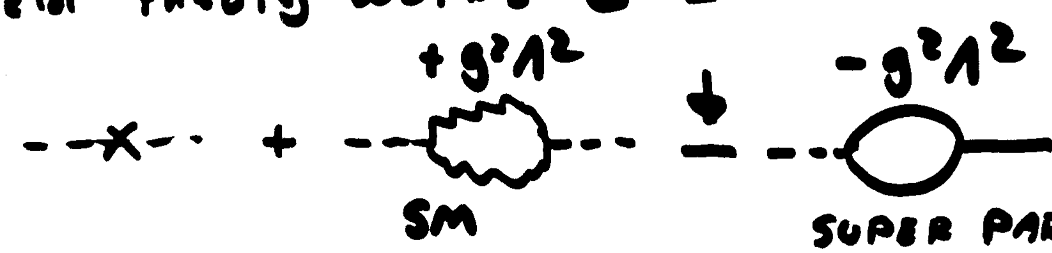
implies $R = M_F (M_{pl}/M_F)^{2/n}$

III Supersymmetry (Quad. div.)

Scalars are fundamental

field theory works @ $E > 100$ GeV

$m_H^2 =$



3 Classic Naturalness Criteria

1937: DIRAC "*No small numbers.*"

$$\lambda_i = \mathcal{O}(1)$$

} $\lambda_e = \mathcal{O}\,10^{-5}$
$\mathcal{L}_{eff}$?

1978: WILSON "Observable properties of a theory should be stable against minute variations of the fundamental parameters."

1980: 't HOOFT " $\alpha_i(\mu) << 1$ is only allowed if $\alpha_i(\mu) = 0$ increases the symmetry of the system."

} [redacted]

We will impliment a modified form of the Wilson / Susskind criterion.

1990's Measurable quantities should not be unusually unstable against minute variations of the fundamental parameters.

[illegible]

BEWARE OF THEORISTS BEARING LIMITS FROM NAT.

Unsuccessfull attempts to quantify naturalness

EENZ
BG

$$C = \frac{x}{y}\frac{\partial y}{\partial x}$$

↑ naive Wilsonian sensitivity parameter

$$\frac{\delta y}{y} = c\,\frac{\delta x}{x}$$

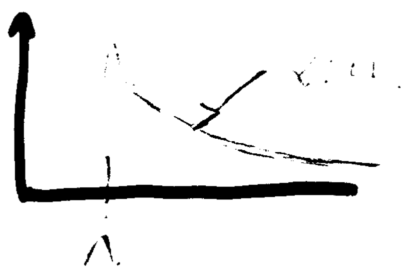
y = observable
x = "fundamental" parameter

$$m_s^2 = m_1 g^2 - \Lambda^2$$

$$C = 2\,\frac{m_1 g^2}{m_s^2}$$

So, why is this problematic?

$$M_{prot} \approx \Lambda_{QCD} = M e^{-\frac{8\pi^2}{b_3 g^2(M)}}$$



$$C = \frac{4\pi}{b_3}\left(\frac{1}{\alpha}\right) \gtrsim 100!$$

$$\frac{\delta m_p}{m_p} \gtrsim (100)\,\frac{\delta g}{g}$$

EWSB $$\frac{1}{2}m_Z^2 = \frac{m_{H_D}^2 - t_\beta^2 m_{H_U}^2}{t_\beta^2 - 1} - \mu^2$$

Define a smooth metric on parameter space

$$dP = f(x)\frac{dx}{x}$$
$$= f(x)\,g(y)\frac{dy}{y}$$

probability that y lies wi a scale invariant interval dy/y for a given x

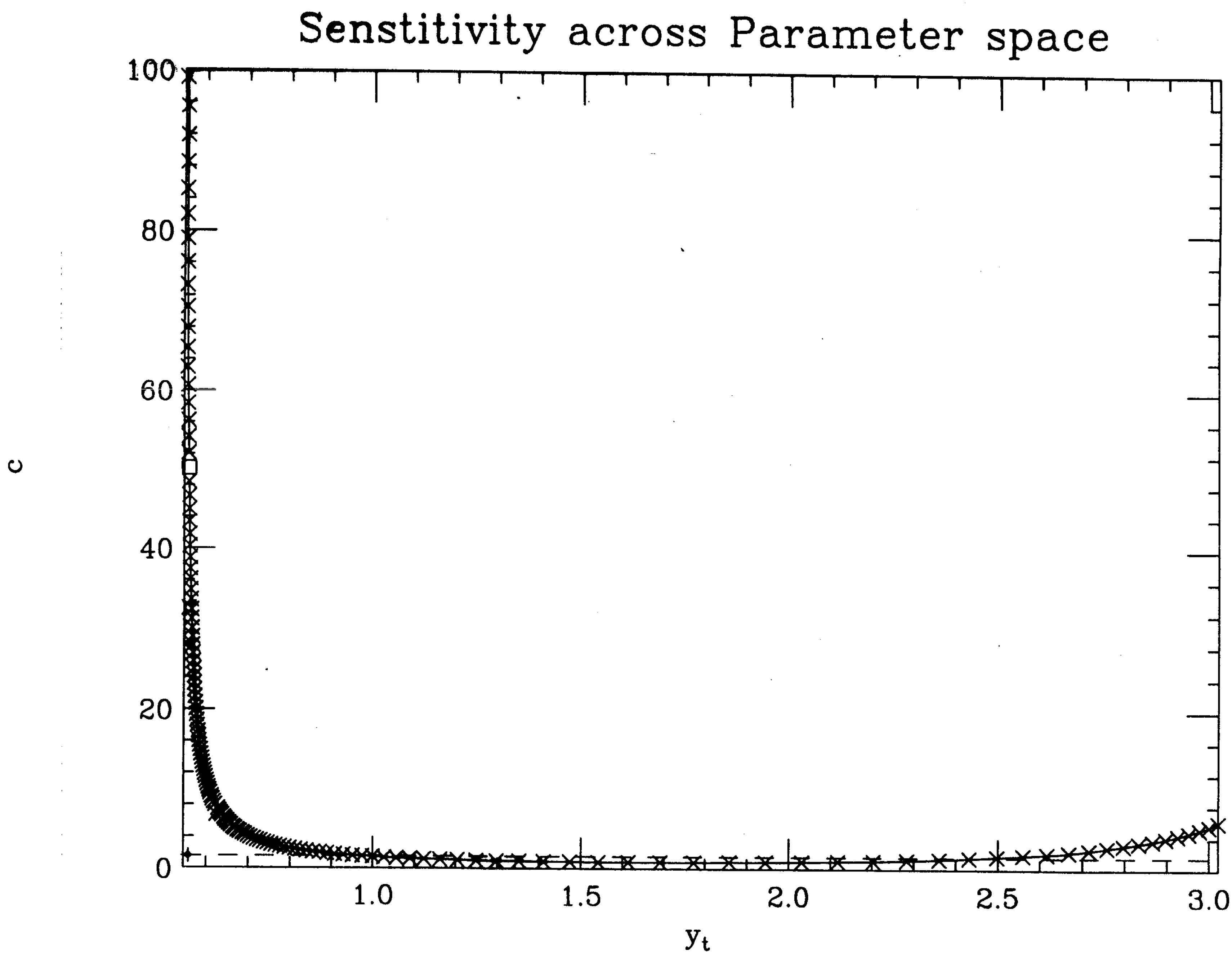
$$g(x) = \left[\frac{x}{y}\frac{dy}{dx}\right]^{-1}$$

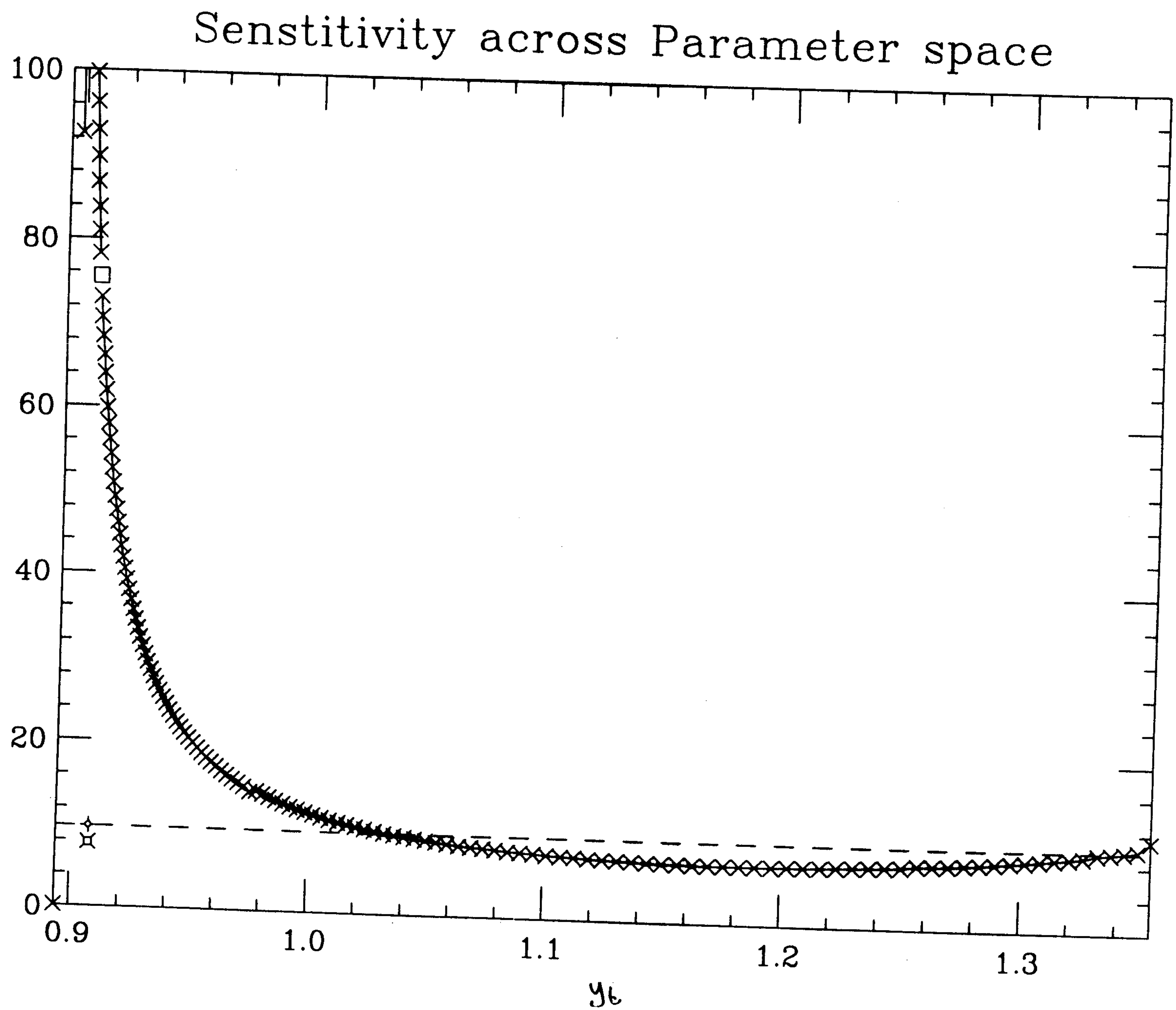
Relative probability of observing y

$$\frac{g}{\bar{g}} = \frac{c^{-1}}{\int \frac{dx}{x} f c^{-1}}$$

$$\gamma = \frac{\bar{g}}{g} = \frac{c}{\bar{c}}\ , \quad \bar{c}^{-1} = \frac{\int \frac{dx}{x} f\, c^{-1}}{\int \frac{dx}{x} f}$$

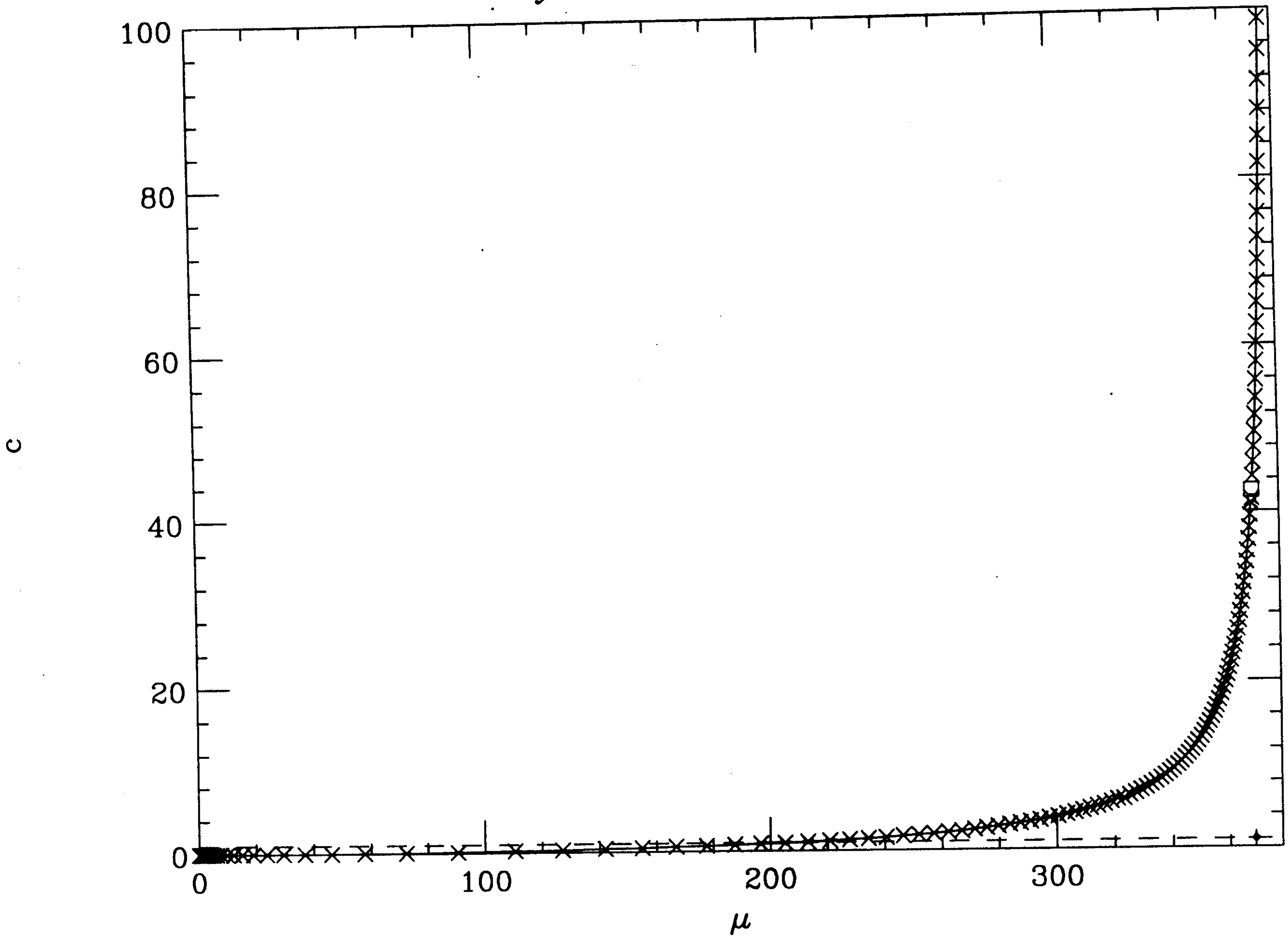
The observed value of y is fine-tuned when minute variations in fundamental parameters "x" lead to unusually large variations in y

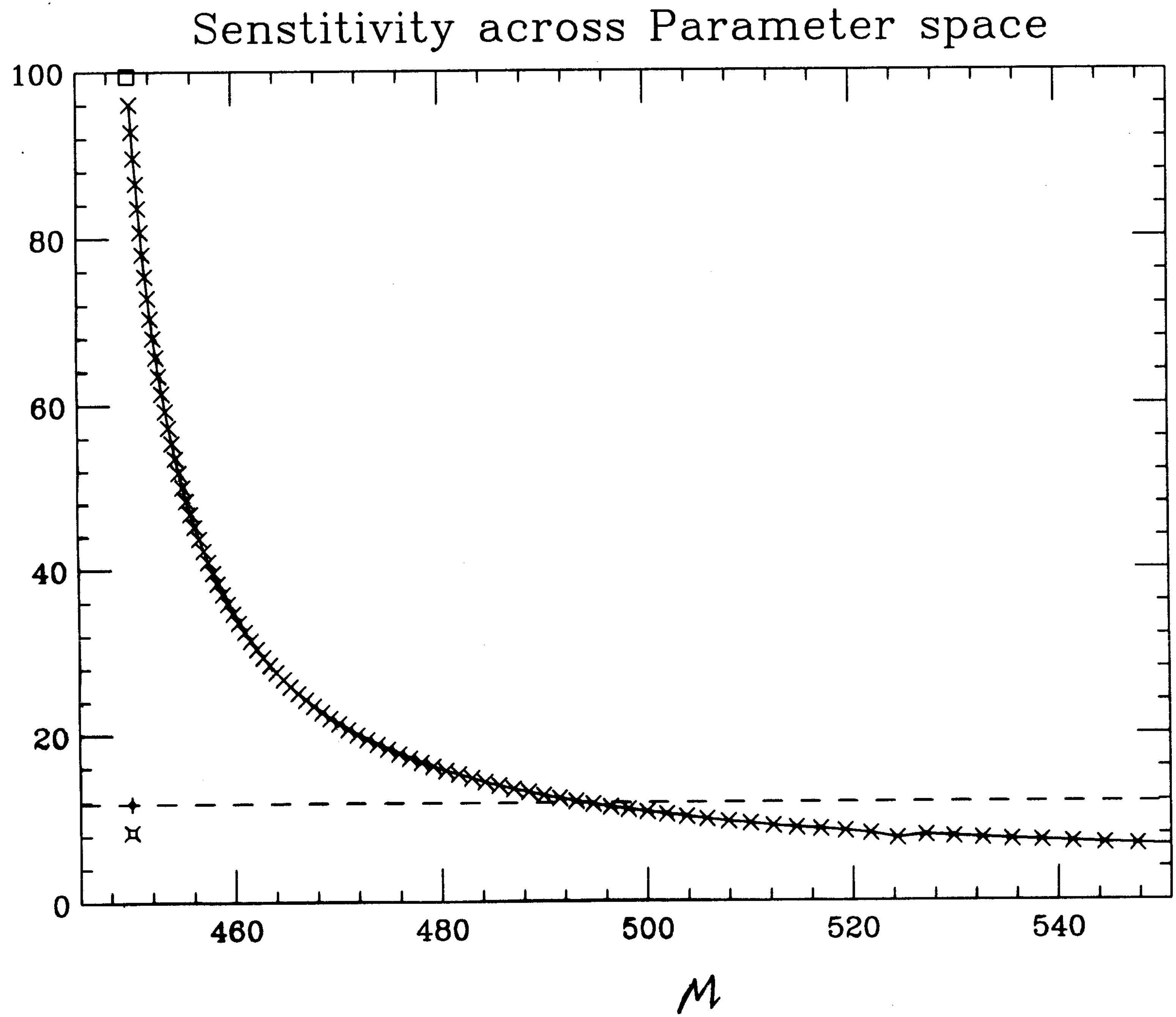

Senstitivity across Parameter space
100
80
60
40
20
0
c
1.0
1.5
2.0
2.5
3.0
y_t

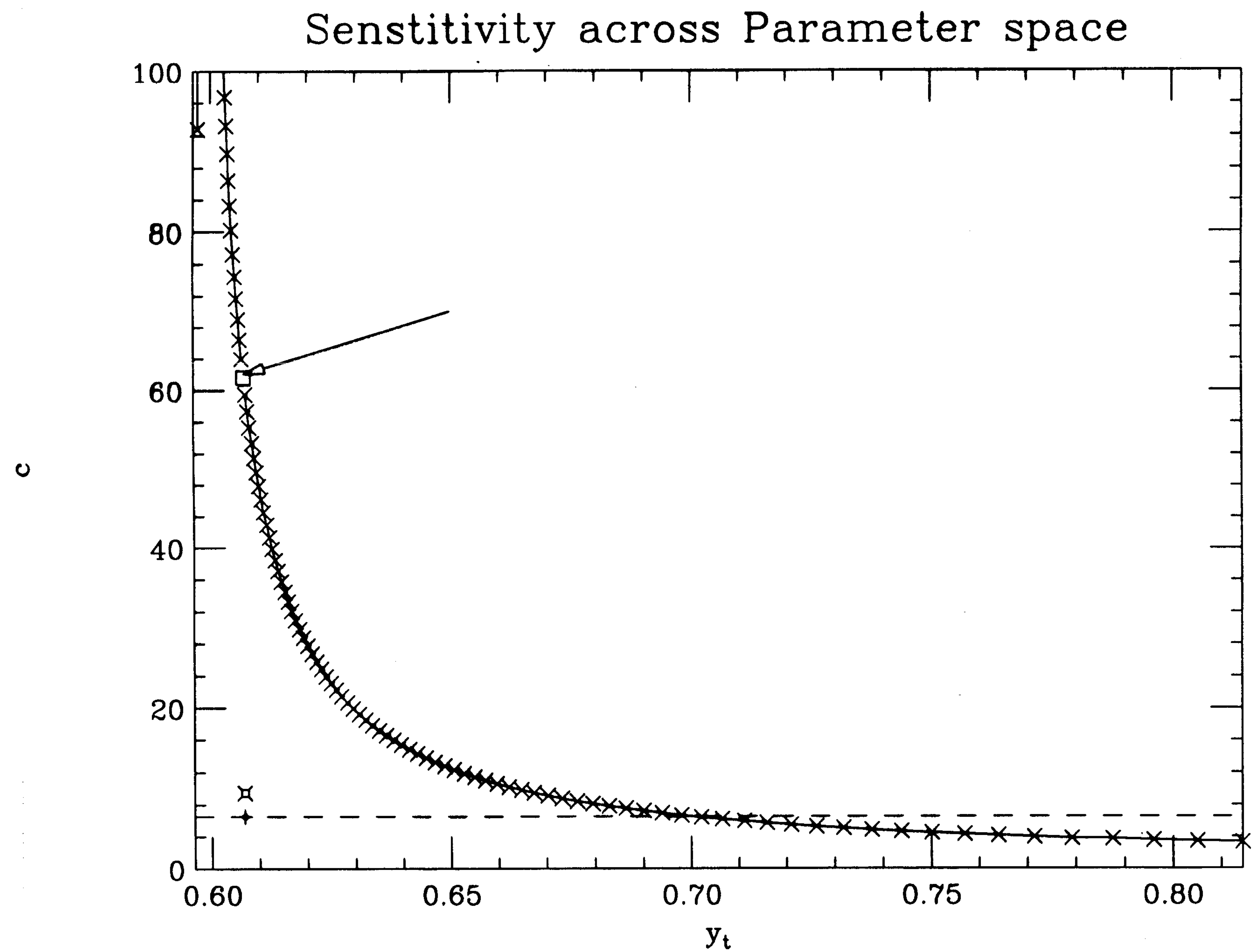


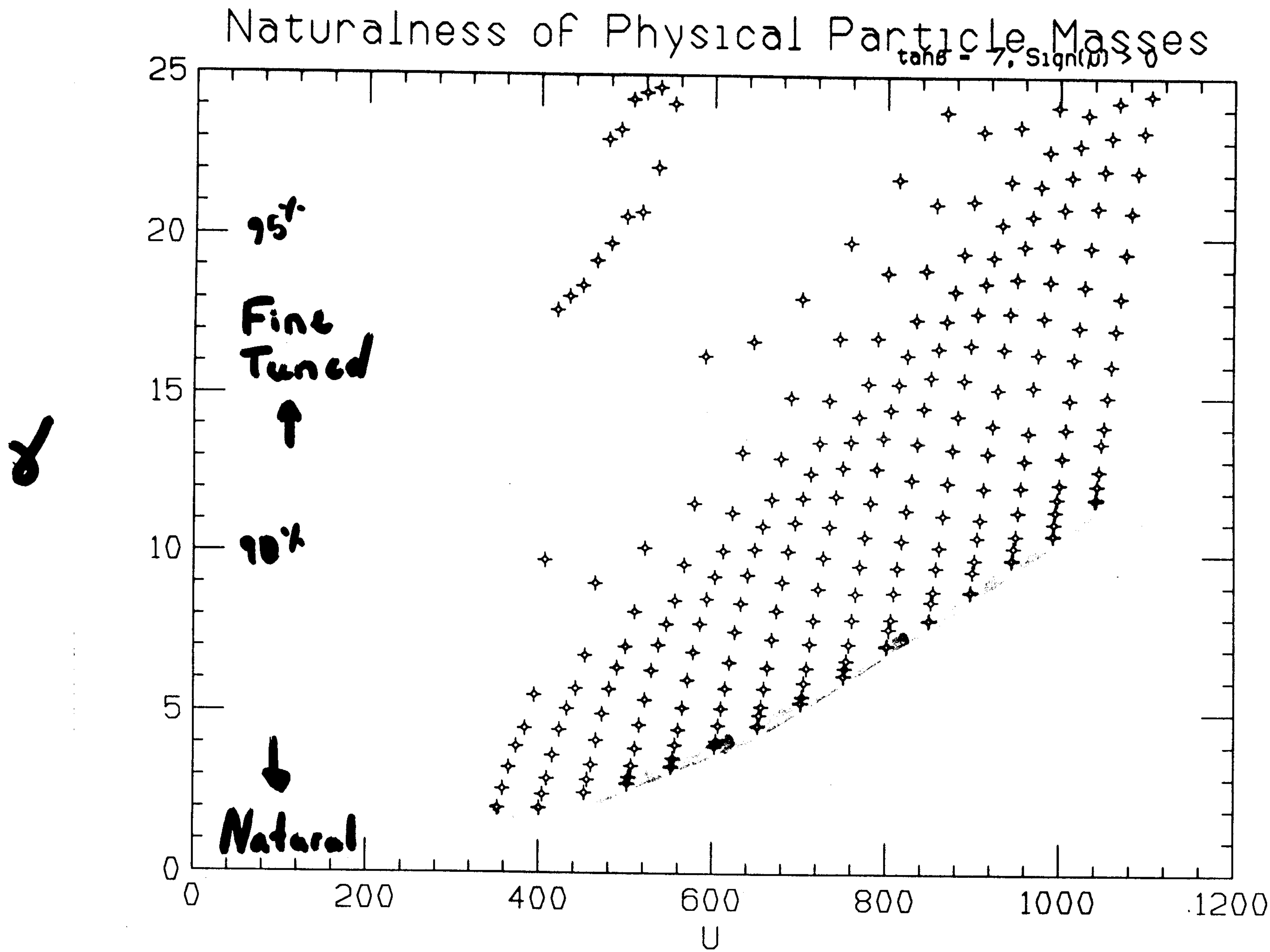
Senstitivity across Parameter space
100
80
60
40
20
0
0.9
1.0
1.1
1.2
1.3
y_t

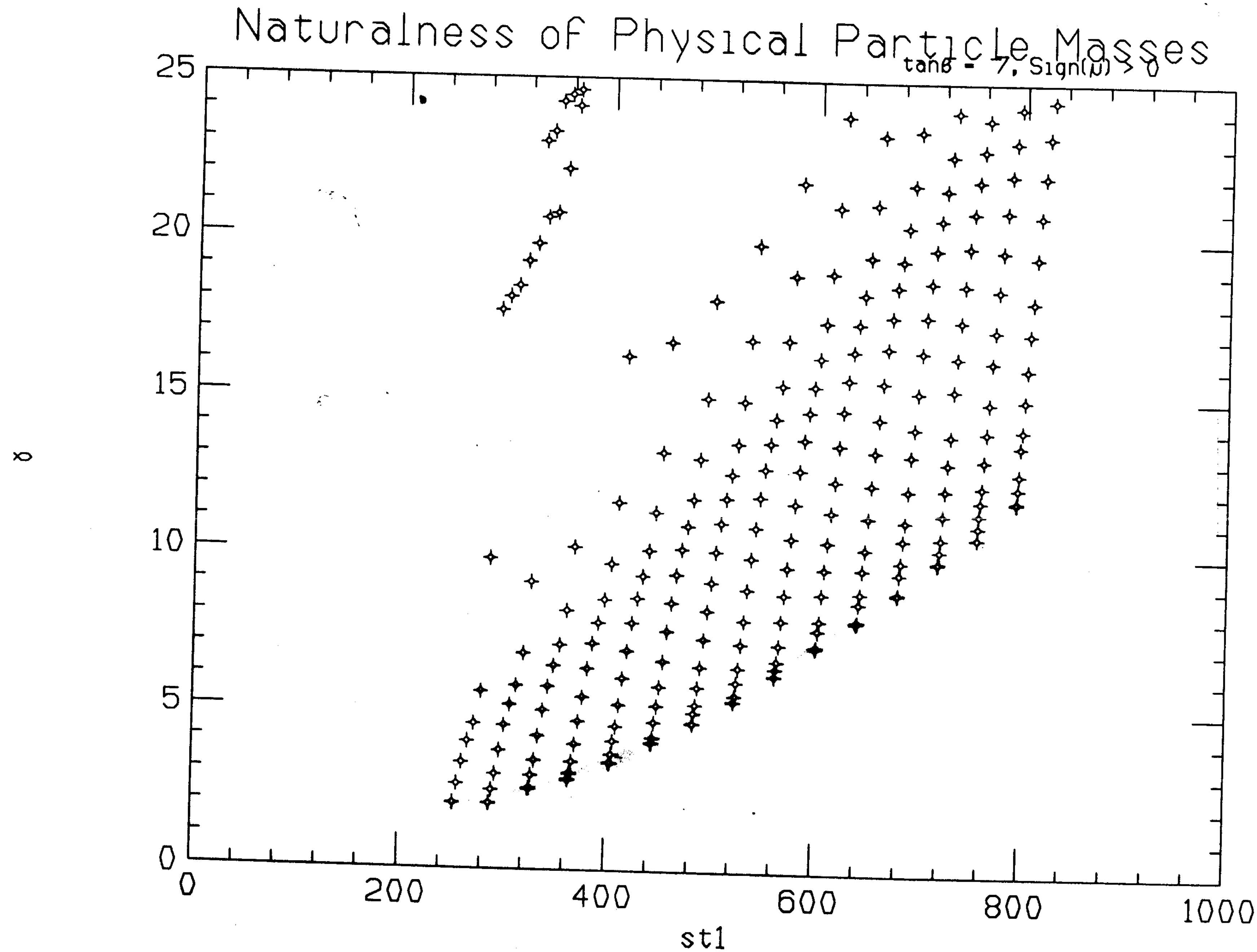
Senstitivity across Parameter space



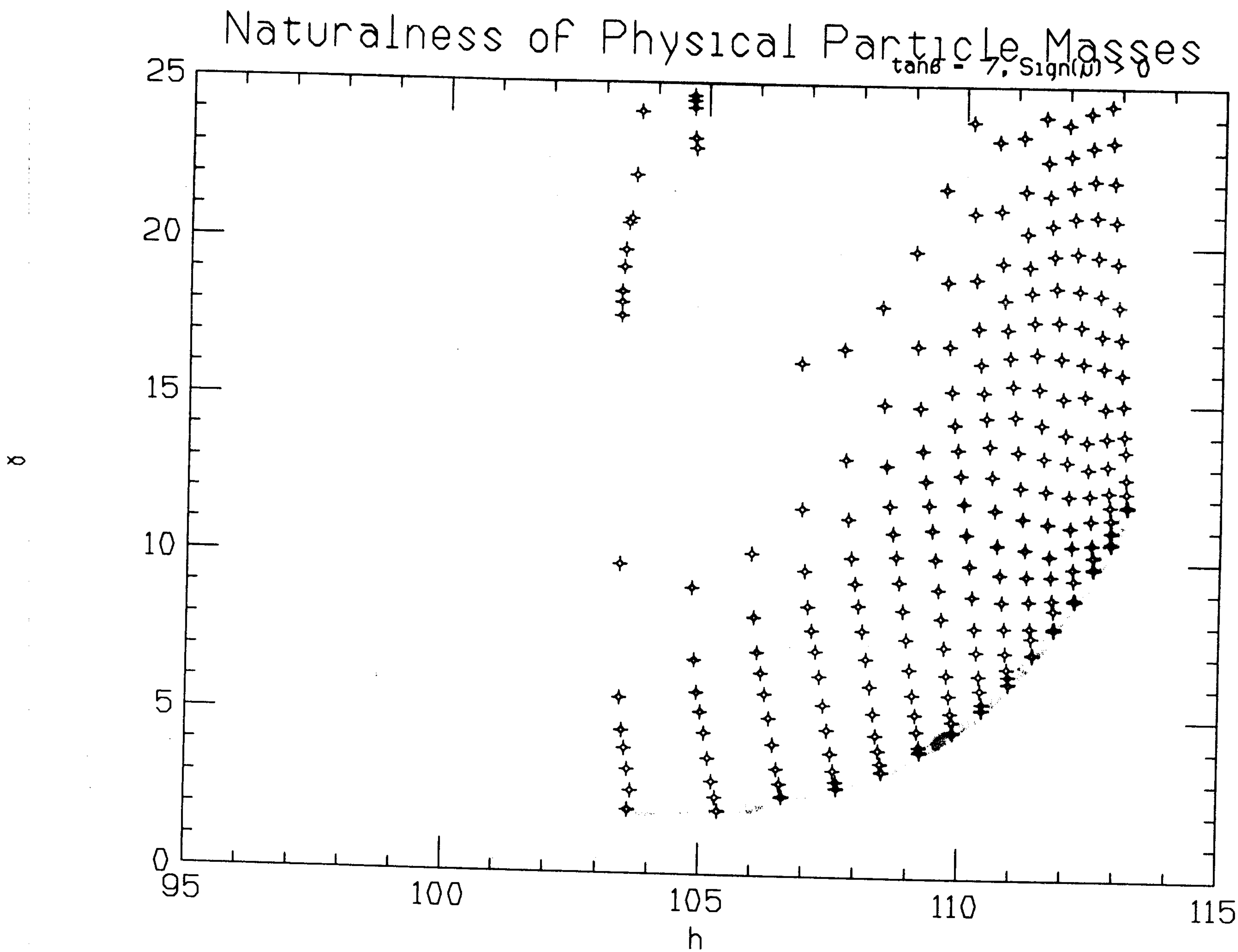

Senstitivity across Parameter space
100
80
60
40
20
0
460
480
500
520
540
M


Senstitivity across Parameter space
100
80
60
40
20
0
0.60
0.65
0.70
0.75
0.80
y_t
c

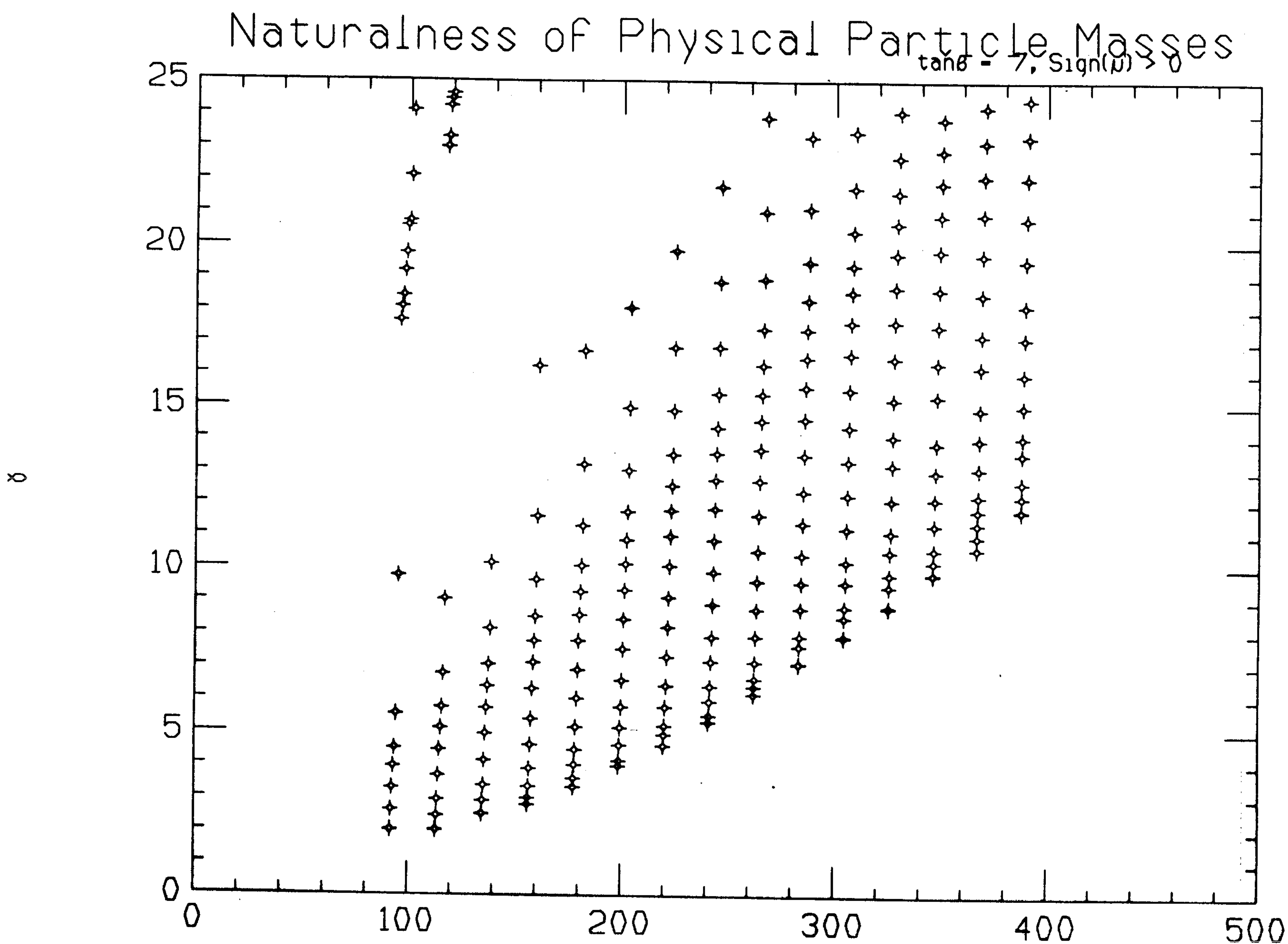

Naturalness of Physical Particle Masses
tanβ = 7, Sign(μ) > 0
25
20
15
10
5
0
0
200
400
600
800
1000
1200
U
95%
Fine
Tuned
90%
Natural



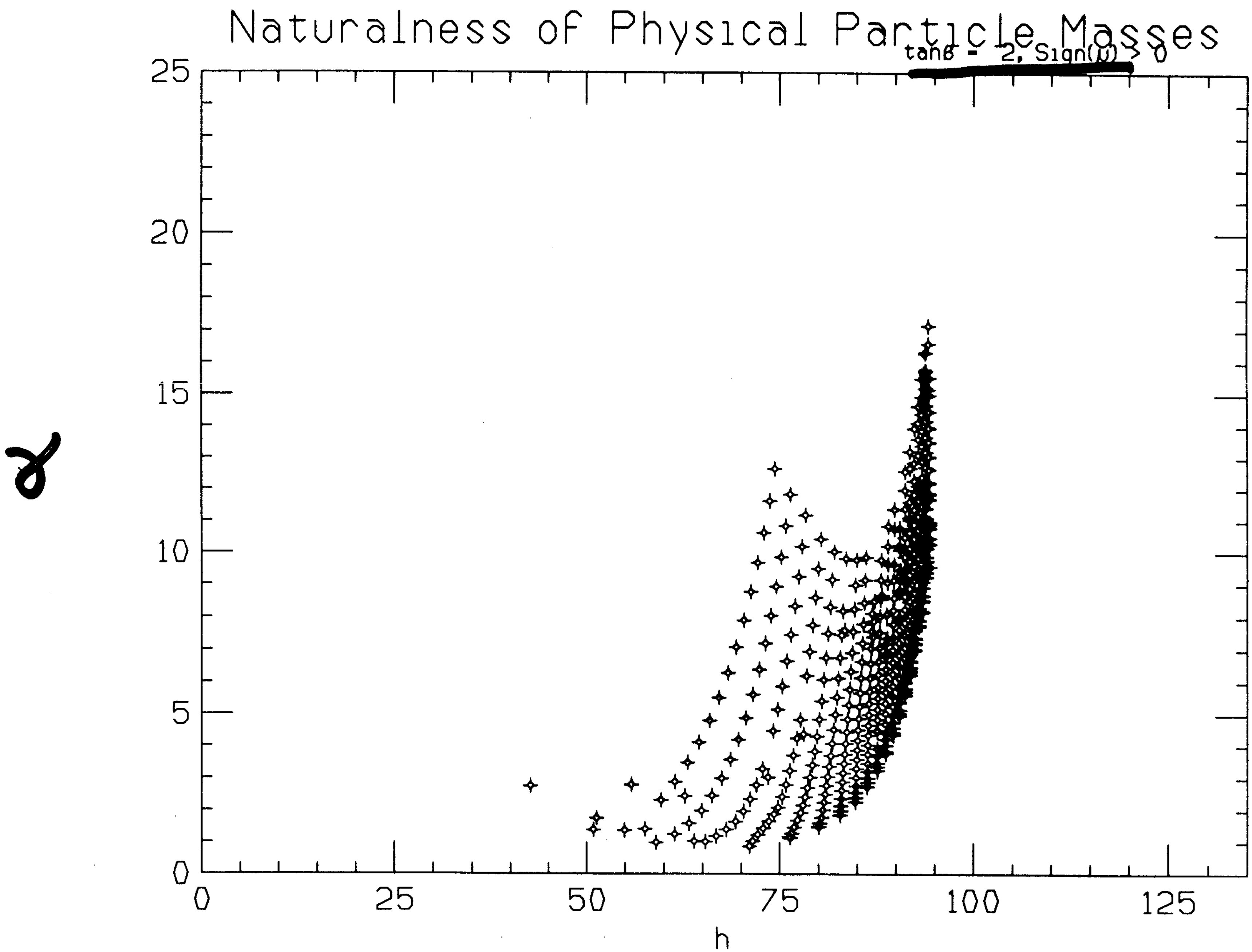
Naturalness of Physical Particle Masses
tanβ = 7, Sign(μ) > 0
25
20
15
10
5
0
0
200
400
600
800
1000
st1

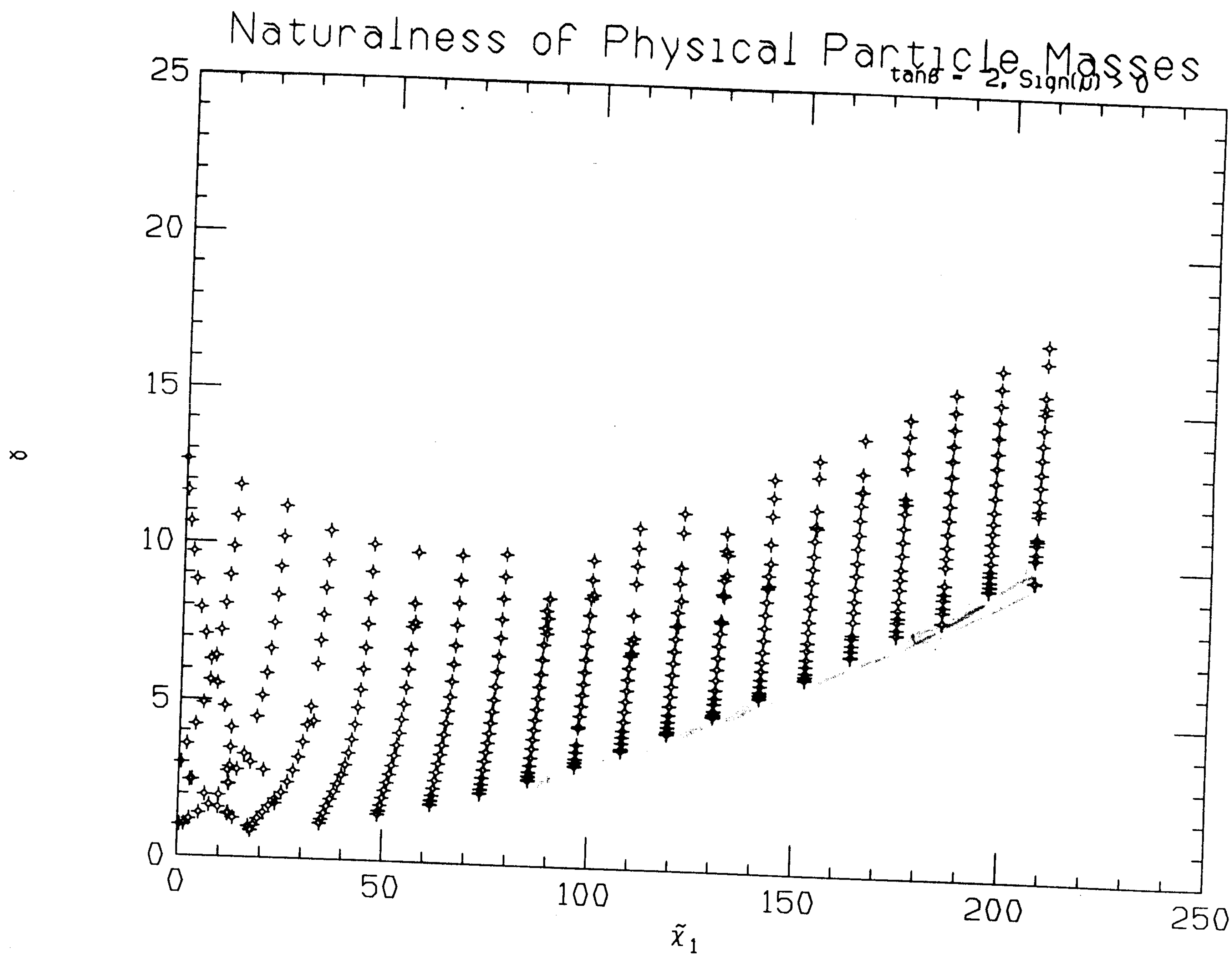


Naturalness of Physical Particle Masses
tanβ = 7, Sign(μ) > 0
δ
h
0
5
10
15
20
25
95
100
105
110
115



Naturalness of Physical Particle Masses
tanβ = 7, Sign(μ) > 0
δ
0
5
10
15
20
25
0
100
200
300
400
500


Naturalness of Physical Particle Masses
tanβ = 2, Sign(μ) > 0
γ
0
5
10
15
20
25
0
25
50
75
100
125
h



Naturalness of Physical Particle Masses
$\tan\beta = 2,\ \mathrm{Sign}(\mu) > 0$
25
20
15
10
5
0
0
50
100
150
200
250
δ
$\tilde{\chi}_1$

Castaño & Anderson

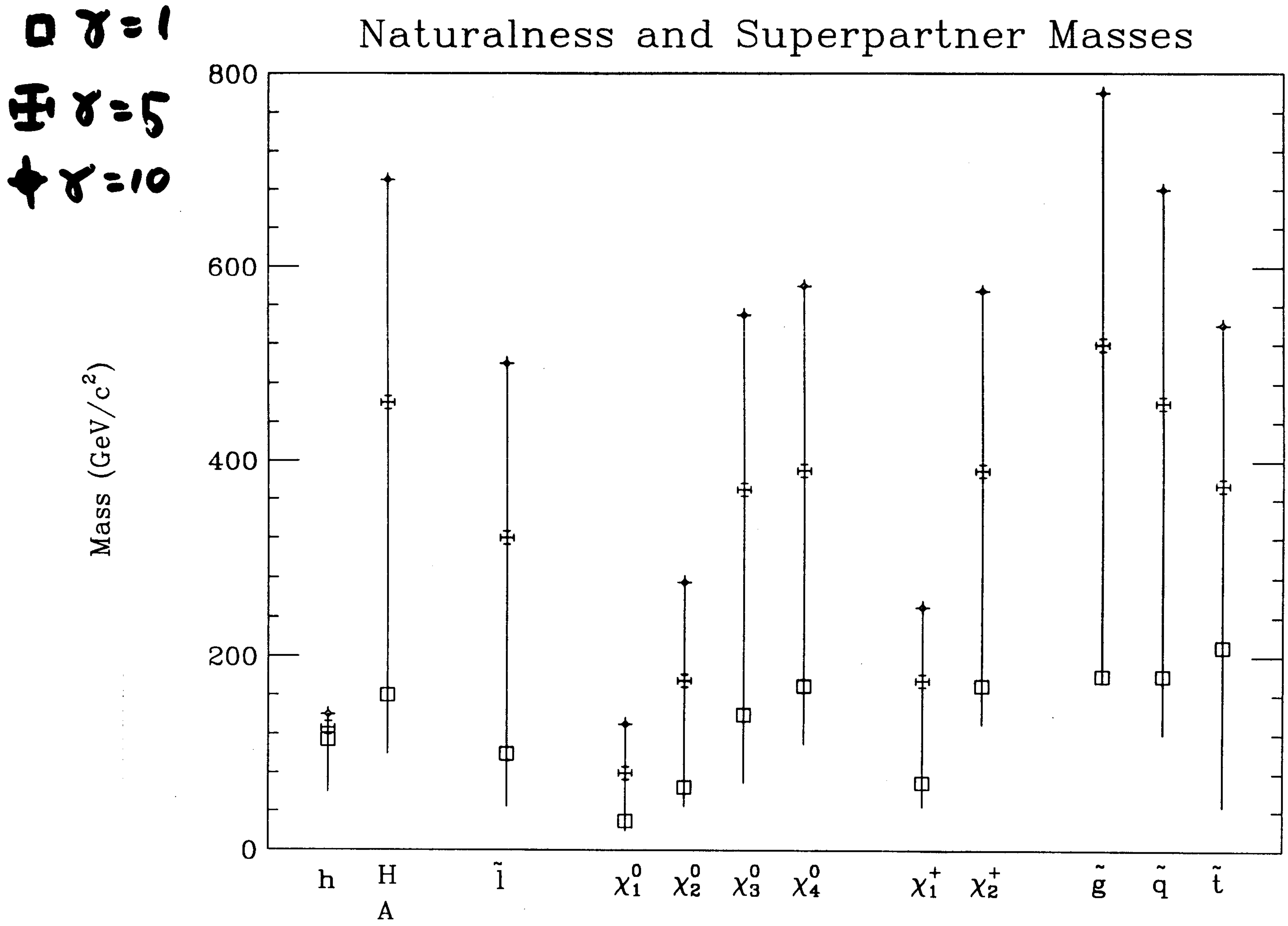
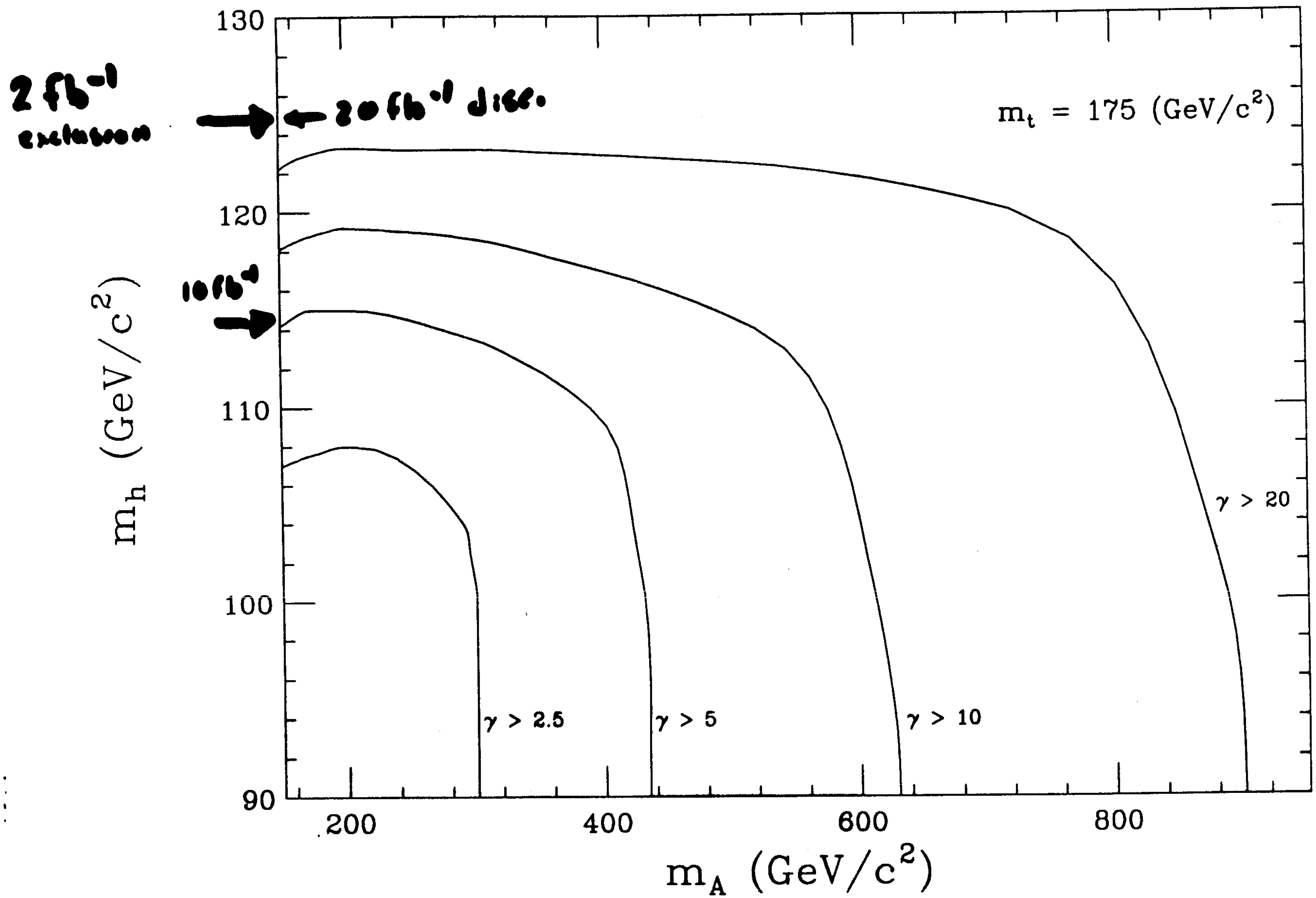
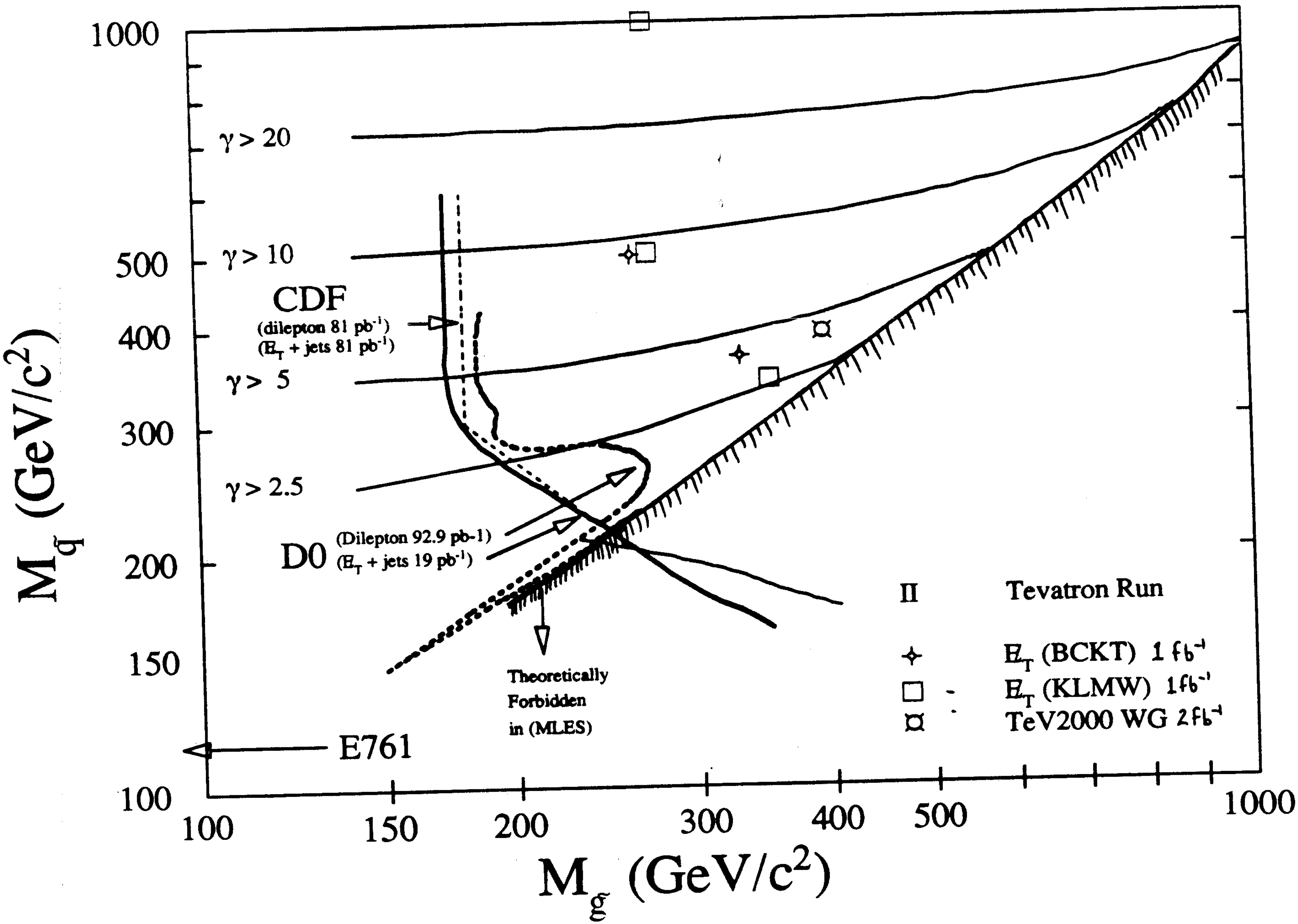


Figure 2



130
120
110
100
90
200
400
600
800
m_h (GeV/c^2)
m_A (GeV/c^2)
m_t = 175 (GeV/c^2)
γ > 2.5
γ > 5
γ > 10
γ > 20
2 fb^{-1} exclusion
20 fb^{-1} disc.
10 fb^{-1}

Tevatron Searches



Conclusion and Outlook:

- If the next level beyond the SM is SUSY
  - All sparticles will be accessible to the LHC
  - The relevant scales are all $< TeV$
  - Beware of theorists with strongly time dependent naturalness limits

Tenable Scenarios for SUSY with new physics > 1 TeV

- Scenarios motivating a scale $> M_{weak}$
  - Physics related to Extra Dimensions
  - Messengers

- Scenarios with add hoc New Scales
  - Heavy 1st & 2nd Generation Superpartners (FCNC)
  - Heavy Vectorlike reps